7.—Round Australite Core from Graball, Western Australia

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A large round australite core found at Graball, Western Australia weighs 168 grams and is 57 mm in diameter and 34.5 mm thick. It is the fourth largest known australite and the second largest known round core.

A sculpture pattern of flow swirls and pits on the posterior surface is apparently of primary origin, produced in an extra-terrestrial environment.

Meandrine grooves, crater-like depressions, and minute pits on the anterior surface, are due largely to differential solution-etching in soils. They are limited to a thermally stressed surface left after considerable ablation of the primary form. Ablation was by frictional heating during aerodynamically stable transit at ultrasupersonic velocity through the earth's atmosphere. A well-developed flaked equatorial zone was evidently initiated circumferentially around the edge of the specimen during the end phases of high-speed infall, and subsequently became etched by terrestrial weathering.

Introduction

A large round australite core, discovered in 1952 on the roadside near Graball telephone exchange, approximately seven miles north-west of Mt. Walker, near Narembeen, 155 miles east of Perth, Western Australia, has recently been brought to notice through the courtesy of Mr. W. H. Cleverly of the School of Mines, Kalgoorlie, and Mr. W. Meacock of the Mt. Walker Government School, Western Australia.

The specimen, weighing 168 grams, was kindly loaned by the owner, Mr. W. Berry, of Mt. Walker, Western Australia, for examination. Only three other australites are known to be heavier than this specimen, each of them weighing over 200 grams.

Three casts of the specimen, prepared in "Artificial Stone" at the Geology Department, University of Melbourne, are lodged: one in the University of Melbourne geological collection, one in the tektite collection of the National Museum of Victoria, and one in the author's private collection of tektites.

Size of Specimen

The round australite core has a diameter of nearly 57 mm and a depth (thickness) of 34.5 mm. It weighs 168.28 grams, a value exceeded by only three other australites. The largest is a fractured oval-shaped form weighing 238 grams from Warralakin, Western Australia (Baker 1962*a*); the next is a large round australite core weighing 218 grams from Lake Yealering, Western Australia, described by Fenner (1955) as a lens form; the third largest is a boat-shaped form weighing 208.9 grams from Karoonda, South Australia (Fenner 1955, Plate VII Nos. 3 and 4). The Graball specimen is thus the second largest known round core type of australite; it shows comparable sculpture patterns to those on the larger Lake Yealering round australite core figured by Fenner (1955, Plate VII, Nos 1 and 2).

The specific gravity of the Graball specimen, determined in distilled water (T = 19.3°C.) on an air-damped chemical balance, is 2.434. From the specific gravity—silica relationships of tektites, this value indicates a silica content of approximately 72 per cent.

Structure and Sculpture

The specimen is reasonably well preserved, and shows the following features:

Posterior surface.—The posterior surface (Plate I, A), which remained directed back along the flight path during ultrasupersonic atmospheric flight earthwards, shows no features assignable to the effects of aerodynamic heating and ablation or aerodynamic sculpturing, hence its sculpture pattern is considered to have been developed in an extra-terrestrial milieu. It has been but slightly modified by terrestrial erosion since landing on the earth's surface a few thousand years ago.

An artificially chipped area around the region of the rear pole on the posterior surface, is approximately 10 mm in diameter. It reveals the characteristic vitreous lustre of freshly broken tektite glass (Plate I, A). The subconchoidal fracture surface shows secondary ripple fracture lines and carries five "knobs" up to 1.5 mm in diameter which are unusual structural features on the broken surfaces of fractured australites generally.

The rest of the posterior surface has principally a primary sculpture pattern of flow swirls showing schlieren, in places arranged in complex fold-like structures. Round to elongated pits averaging 1 mm in diameter, occur towards the edges of the posterior surface (Plate I, A). After removing soil constituents from the pits, their walls revealed a lacquer-like lustre produced by a process of natural solution-etching which has also brought out some of the fine schlieren on the pit walls. The general surface of the tektite at the level of the pit openings, however, shows a rather duller, almost sub-vitreous lustre.

Flaked equatorial zone.—The flaked equatorial zone (Plate II, A and B) occurs circumferentially in the mid-regions of the specimen as viewed in side aspect. It is approximately 10 mm broad. The rim separating it from the

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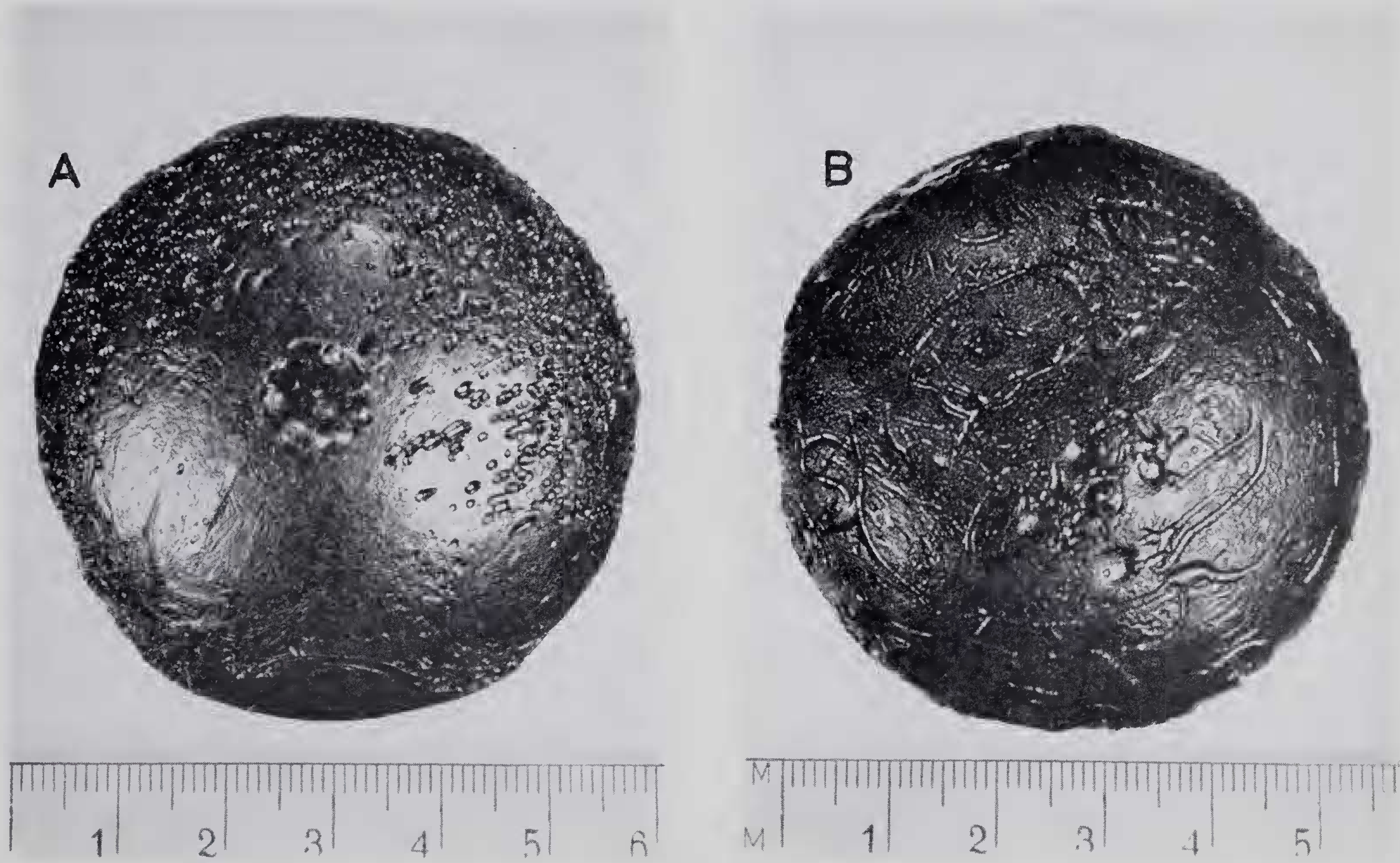

PLATE I

Round australite core from Graball, Western Australia.

A—posterior surface showing bubble pits and flow swirls (darker area in centre of photograph is a fracture surface).

B—anterior surface showing crater-like depressions and meandrine grooves (the surface flattens somewhat from the centre to the top of the photograph).

Scale is in centimetres and millimetres. Photographs by Alfred A. Baker.

posterior surface (uppermost in Plate II) is sharply defined, but the anterior surface (lowermost in Plate II) and the flaked equatorial zone merge more gradually into one another.

Vertical, oblique, and less commonly meandrine short grooves 2 mm long and 1 mm wide, and longer straight grooves up to 10 mm long and 1 mm wide, cut across the flaked equatorial zone, and mainly trend parallel with the breadth. Like the pits on the posterior surface, these grooves occasionally reveal fine schlieren crossing their walls at various angles.

Anterior surface.—The anterior surface (Plate I, B), which was fully exposed to aerodynamical forces during high-speed flight through the earth's atmosphere, remained directed forward down the flight path as long as the specimen was maintained in aerodynamic stability at the high entry velocities.

Meandrine (some "vermicular"), straight, and curved grooves on the anterior surface vary in length and average about 1 mm in width (Plate I, B). Sometimes they are S-shaped in plan (left-hand side, Plate I, B), occasionally J-shaped. In cross sectional aspect they are largely U-shaped. The walls of some plainly reveal a few small etch pits; more frequent are fine flow lines that cross the grooves at right angles, or obliquely, or sometimes trend parallel with their length. Occasional grooves are at a slightly lower level than others, and neighbouring grooves sometimes cross or merge with one another in places.

A few depressions 3 mm across, 0.5 mm deep, and circular in outline (lower central portion, Plate I, B) are crater-like compared with smaller pits (right, central portion, Plate I, B). They sometimes carry smaller pits and occasional fine flow lines that cross their walls in random directions.

The asymmetrical silhouette of the anterior surface observed from one side aspect of the specimen (Plate II, B), evidently has arisen from weathering. This gives a flattening effect which is faintly discernible in plan aspect (top portion of Plate I, B).

Curvature and Volume

The radii of curvature of the posterior (R_B) and of the anterior (R_F) surfaces were determined from a silhouette tracing equivalent to a cross section containing the polar axis of the specimen (i.e. equivalent to an enlarged silhouette trace of Plate II, A).

The values so obtained are:

R_B = 4.0 cms (40.25 mm).

R_F = 3.7 cms (36.75 mm).

The posterior surface is evenly curved in all directions radially outwards from the rear pole of the specimen. Its arc of curvature corresponds with that of a constructed circle with radius 4.0 cms, but only about 28 per cent. of the original curved surface remains after ablation, assuming the parent form was a sphere.

The arc of curvature of the anterior surface was not even in all directions outwards from the front pole (cf. Plate II, B), so the radius of curvature was determined from a silhouette tracing of the most regular curvature shown in one side aspect (cf. Plate II, A).

The area of the front surface ($2\pi rh$), where h is the height of the anterior cap above the rim of the specimen, was calculated as 58.13 cm^2 assuming that the area of the front surface is equivalent to the area of the cap of a smooth sphere. This represents the frontal area projected in the flight direction during the closing stages of the aerodynamic heating process. The height of the anterior cap is 2.5 cms, and the height of the posterior cap is 0.95 cms; together these constitute the depth or thickness (3.45 cms) of the australite.

The volume of the specimen is 69.1 cm^3. The volume of a sphere of australite glass with R = 4.0 cms and of specific gravity the same as that (2.434) determined for the residual australite shape (large round core), was calculated as 268.1 cm^3. This is not quite $2\frac{1}{2}$ times the volume of the largest round core so far recorded from the Port Campbell district some 1,500 miles distant in Victoria (Baker 1962*b*).

Loss by Ablation

If the parent form of the large round australite core from Graball, Western Australia was a sphere, or a spheroid close to a sphere then the volume of tektite glass lost (a) during entry at high speed, by ablation, and (b) during the few thousand years that the specimen has lain exposed to weathering on the earth's surface, amounts to 199 cm^3, this being the difference between the parent sphere volume and the volume of the residual australite round core; it represents a loss of approximately three quarters of the primary form. Thus, as a consequence of aerodynamic heating with attendant ablation and fusion stripping, followed by terrestrial erosion, only 25.8 per cent of the original form remains. Allowing for the small chip lost by artificial fracturing (see central portion of Plate I, A), this value can be rounded-off at 26 per cent.

Although it is impracticable to assign definite proportions to either of these processes causing loss of australite glass since initial entry into the atmosphere, largely because of the unknown loss by erosion, it is expected that the combined effects of ablation and fusion stripping and possibly some stress exfoliation in the subsonic region of the flight path, significantly dominated loss by subsequent terrestrial weathering. Assuming, as a generality, that erosional loss in the Australian strewnfield amounted to at least ten per cent. of the tektite glass that reached the earth's surface, it is apparent that over 70 per cent. of the Graball primary form was consumed by aerodynamic ablation. This is in accord with the calculated ablation losses of other primary spheres from which large round cores were produced (Baker 1962*b*).

As measured graphically, and calculated from $2(R_B)$—D where R_B is the radius of curvature of the posterior surface, and D the depth of the specimen measured from the back to the front pole, the depth of ablation from the front pole of the reconstructed primary sphere to the front pole of the remnant australite core, is 45.5 mm.

A

B

PLATE II

Round australite core from Graball, Western Australia.

A—side aspect showing flaked equatorial zone separating posterior (uppermost) from anterior (lowermost) surfaces.

B—side aspect in a position normal to that of (A) above, showing flattened arc of curvature of anterior surface in lower left portion of the photograph.

Most grooves crossing the flaked equatorial zone trend parallel with the line of flight which was in a direction from top to bottom of the photograph.

Scale is in centimetres and millimetres. Photographs by Alfred A. Baker.

This is 56.9 per cent. of the original sphere diameter, and thus comparable with the average percentage value (56.5 per cent.) for ten round australite cores from Port Campbell, Victoria (Baker 1962*b*). Among other things, this is proportional to the aerodynamic heating (*fide* Dr. Dean R. Chapman, N.A.S.A., U.S.A.).

Compared with the depth of ablation (7.5 mm) of a hollow australite of comparable diameter containing an eccentrically disposed internal cavity (Baker 1961), the depth of ablation along the polar axis of the solid australite core from Graball has been six times as great. The indication is that the hollow form was therefore a much more effective dissipator of the frictional heat input during aerodynamically stable transit through the earth's atmosphere.

By comparison with the average for perfectly developed, excellently preserved australite buttons having well-formed circumferential flanges (Baker 1962*b*), and with the value for the hollow australite which is also perfectly developed and very well preserved (Baker 1961), the aerodynamic heating (determined from A.H. $= k/\sqrt{R_F}$, where R_F is the radius of curvature of the anterior surface) for the large, well-developed, reasonably well preserved, round australite core of solid tektite glass from Graball, Western Australia, is 0.520 (see Table I).

TABLE I

Australite Shape Type	Locality	Aerodynamic Heating
Perfect flanged buttons	Port Campbell, Victoria	0·920*
Large round core (solid glass)	Graball, Western Australia	0·520
Large round hollow form	Horsham, Victoria	0·187

* This is an average value for 23 perfect australite buttons, the range for which was 0.86 to 1.09.

The aerodynamic heating value for the hollow form is lowest, and equal to only one fifth that for the perfect australite buttons. The value for the large solid core is intermediate and its aerodynamic heat input was a little over half that for perfect buttons, approximately two and three quarter times greater than the input for the hollow round australite.

Relative to the perfect flanged buttons, which are smaller, the solid round core from Graball has a larger mass per unit frontal area, hence, during high speed earthward flight, more of the aerodynamic heat received was dissipated, largely by radiation. The amount radiated, however, was considerably less than for the hollow round australite from Horsham.

Conclusions

The sculpture of the posterior surface of the large, round australite core from Graball, Western Australia is evidently primary and of extra-terrestrial origin; unlike most other large australites from the more westerly parts of the Australian strewnfield, it has been subjected to less severe weathering by terrestrial agents.

The sculpture patterns of the anterior surface and the flaked equatorial zone are secondary. The curvature of the anterior surface was largely determined by aerodynamic sculpturing during frictional heating processes arising from high speed, aerodynamically stable transit through the earth's atmosphere. Evidently all the fused glass from this secondary period of melting was shed almost immediately during flight. There is (i) no evidence on large cores such as this, that ring-wave formations were developed to give flow ridges and flow troughs as on buttons of smaller size (Baker 1962*b*, Plates XII to XIV), (ii) no evidence of flange glass remaining frozen-in circumferentially as on the flanged buttons, and (iii) no evidence that flange glass was present on landing and was subsequently removed by weathering.

Accepting the parent form as having been a sphere of australite glass of 8.0 cms diameter, then more extensive loss of all the melt glass and vapourised glass during aerodynamic fusion has occurred to produce this large core than in forming flanged button-shaped australites from originally smaller spheres. The depth of ablation in the stagnation point (front polar) regions was proportionally much greater than for flanged buttons where all melt glass was not shed, because some was re-frozen in equatorial regions of the ablated smaller spheres to form circumferential flanges. Depths of ablation in forming perfect flanged australite buttons range from 5.5 mm to 16.5 mm, and average 9.5 mm. This is 47.3 per cent. of the diameters of the originally smaller spheres which ranged from 12.7 mm to 27.1 mm and averaged 20.1 mm in Port Campbell specimens (Baker 1962*b*). Depth of ablation (45.5 mm) of the sphere from which the large round core from Graball was produced, represents 56.9 per cent. of the original sphere diameter, i.e. approximately 10 per cent. more.

Since not all of the melt glass was shed in forming the australite buttons, and a relatively substantial amount went into the building of the circumferential flanges, there was an increase in the frontal area. This increase was equal to the area of the anterior surface of the newly generated circumferential flange. Consequently, flange formation led to reduced aerodynamic heating (*fide* Dr. Dean R. Chapman) as an outcome of increased amounts of drag arising from increased frontal area. Such a process did not occur in the large core types of australites, so that the aerodynamic heat input was maintained at a steady rate as long as high enough velocities prevailed. This being so, greater aerodynamic heating leading to melting and ablation was experienced than in the phases of button generation when circumferential flanges were formed.

The present sculpture pattern of grooves, craters and pits on the anterior surface, and probably also on the flaked equatorial zone, is fundamentally a result of natural solution-etching developed after landing on earth surface. It is not easy to assess how far a process of exfoliation on cooling may have affected the anterior surface during the final phases of flight, i.e. between the end of the aerodynamic heating stage and the time of impact with the earth.

This may have been interconnected with, or possibly completely superseded by, subsequent spallation from diurnal temperature changes while resting on the earth's surface. After the australite had passed from (1) the phase of flight where ultrasupersonic and then lesser supersonic speeds prevailed, through (2) the transition zone of transonic speeds, and into (3) the subsonic region where much lower speeds supervened for the final few seconds of earthward trajectory, processes of fusion and ablation created by frictional heating had ceased to operate. The last-formed thin skin (1 mm and under) of the forwardly directed surface that was heated and softened at the end of this stage of flight, then cooled rapidly in the lowermost region of the atmosphere. It was not soft on impact with the earth, as deduced from the available evidence, but compared with the underlying glass, it would have been in a relatively highly stressed condition. Such a crust would tend to exfoliate in thin layers from the anterior surface, either before, and/or after landing. This would result in exposure of a sub-surface of the anterior surface to which the secondary process of aerodynamic heating had not penetrated. Gradual chemical attack of this surface by terrestrial agents, mainly etchants in moist soils, further modified the anterior surface to produce its present sculpture pattern. If the nature of the exfoliation determined the initial trends of solution-etching, it is no longer evident because of the degree to which etching has advanced.

The indications on the Graball round australite core are that mechanical agents causing modification by abrasion played no major role in the process of terrestrial erosion, unless the somewhat flatter appearance of the anterior surface as seen in one aspect (Plate II, B, bottom left-hand side) is a faceted area arising from abrasion by wind-driven sand and soil. There is no proof that such faceting occurred, although the specimen was collected from a region where soil deflation processes operated to a significant degree in recent geological times, and australites are usually discovered with their anterior surfaces uppermost, a position found by experimentation to be their stable position of rest on the earth's surface.

The most dominant cause of weathering was evidently chemical, with soil solutions acting partly differentially to bring about some directionalized and some random natural solution-etching. The meandrine character of certain of the grooves might be indicative of confined biochemical reactions associated with plant rootlets lying in contact with the top of the specimen as it lay embedded in soil. Such reactions are expected to be more prevalent on the uppermost (anterior) than on the lowermost (posterior) surfaces of australites buried in soils, even though, as deflation progressed in some areas, the posterior surface remained longer in contact with soils on exposure.

Acknowledgments

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